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An alternative dopant-measurement method for analyzing ULE implant

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This article describes an alternative dose-measurement method of analyzing ultra-low energy (ULE) ion implantation. The new technique, which entails the spatial and temporal separation of sampling and ionization by using two powerful plasma sources, results in more efficient ionization and more quantitative measurements with reduced matrix effects.

As seen from the *International Technology Roadmap for Semiconductors (ITRS)* [1], the source/drain junction depth is being reduced each year in order to continue MOS transistor scaling. This year, leading-edge foundries and integrated device manufacturers (IDMs) are scheduled to move 65nm processes into pre-production, while simultaneously developing 45nm processes in R&D. In designing and manufacturing such VLSI devices, the junction depth needs to be kept below 50nm, and doping concentrations in the channel must be high and accurate. To obtain an ultra shallow junction (USJ), the most fundamental trend in ion implantation today is to move implant energies lower so that possible surface damage and channeling can be minimized [2]. This trend makes the determination of USJ depths and implant doses increasingly difficult.

The challenge

Determination of implant dose is critical for enabling foundries and IDMs to examine dose retention during implantation and annealing processes, as well as to calibrate and correlate ion implanters used in different processes within different fabs. Commonly, SIMS is used to determine implant doses, where accuracy is strongly dependent on its depth profiling capability, depth resolution, consistency of ion yield and sputtering rate, and compatibility of the reference standards.

As implantation energy decreases and the critical depth for analysis gets down to tenths of a nanometer or shallower, depth resolution provided by SIMS is gradually becoming marginal relative to the analysis depth, and exact matrix-matched standards are difficult to find. Additionally, many effects that are insignificant to the dose measurement by SIMS when profiling deeper implants, have now become profound. For example, near surface equilibrium phenomenon in the transient region (within the first few nanometers from the surface at least) and ion yield variations associated with native oxide present on wafer surfaces can now all affect the accuracy of the dose measurements by SIMS.

The Saris LA ICP-MS (laser ablation inductively coupled plasma-mass spectrometry) technique we evaluated (**Fig. 1**) has been applied in the semiconductor, electronics, and disk drive industries [3-4]. When it is used for total implant dose confirmation, its measurement approach is not based on depth profiling, thus its dose data reliability is no longer dependent on depth resolution. The reduction in implantation energy and junction depth has little or no negative effect on its dose measurement capability. In fact, ULE implants make the analysis using this technique even less challenging because laser sampling does not have to penetrate very deep, and the ICP-MS signal for the same implant at a given dose is more intense because of less signal dilution by silicon.

LA involves the conversion of solid materials into a plume of neutral atoms, ions, and micro particles by focusing a high-powered and pulsed laser beam onto a wafer surface. The laser in this arrangement is used solely for sampling, and the ions directly produced by the laser are not detected. The plume of materials quantitatively generated by LA is transported in an argon carrier gas to the steady-state ICP plasma (~10,000K) for efficient atomization/ionization (Fig. 1). With such an energetic ionization source, few molecular ions and doubly charged

ions are formed, and the mass interferences that SIMS usually encounters [5] are no longer an issue.

The ions formed in the ICP are essentially atomic and dominated by singly charged positive ions, which are directly proportional to dopant doses implanted in silicon. These atomic ions are subsequently analyzed by a mass spectrometer, either quadrupole-based, or high-resolution magnetic-sector based.

Figure 2 shows a schematic diagram of laser sampling on a wafer and a representative ICP-MS signal profile obtained with a ULE boron shallow implant. The laser sampling depth chosen for the dose measurement is typically a little deeper than implant depth to ensure that nearly 100% of the dopant in silicon is ablated within the selected sampling area. As shown in the figure, the $^{11}\text{B}^+$ signal rises immediately after the pulsed laser beam is directed onto the wafer surface, reaches the maximum, and then levels off to form a plateau, while the laser continuously rasters across the wafer surface. After the laser is switched off, the signal quickly decays to baseline without showing much tailing.

Calibration and standardization

Using NIST-traceable solid standards developed in our laboratory, this Saris LA ICP-MS technique has been found to be suitable for quantifying ULE implant doses. Usually, a minimum of three wafer standards are ablated prior to any implant dose measurements to establish a relationship between the signal intensities and implant doses. The signal intensities (either averaged plateau or integrated area under the signal profile) and implant doses were found to be linearly related, and their relationship may be expressed as simply and straightforward as $Y = aX + b$, where Y is the signal intensity and X is total implant dose, with a and b representing the slope and intercept of the linear calibration curve, respectively. For the dose calibration and measurements, neither complicated calculations nor corrections are necessary. Calibration curves constructed for $^{11}\text{B}^+$, $^{31}\text{P}^+$, $^{75}\text{As}^+$, and $^{121}\text{Sb}^+$ implants have correlation coefficients typically better than 0.995, and their linear dynamic ranges are many orders of magnitude greater.

Accuracy and precision

Sample wafers are analyzed under exactly the same condition as calibration standards. The technique's accuracy and analytical precision have been assessed using ULE $^{11}\text{B}^+$ and $^{75}\text{As}^+$ implants. The representative results with $^{11}\text{B}^+$ implanted at 0.5keV and $^{75}\text{As}^+$ implanted at 2-5keV are listed in the **table**. As shown, the LA ICP-MS results are in excellent agreement with nominal doses calculated based on ion implanter beam currents and the length of time for implant. The load-to-load repeatability or precision is ~2-3%.

Matrix and annealing effects

Solid sampling and ionization in direct wafer analysis are two fundamentally different processes requiring very different optimization conditions [3]. Unlike SIMS analysis, which typically utilizes a single ion beam, the LA ICP-MS technique employs two powerful plasma sources (a laser and an ICP), spatially and temporally separating its ionization from the sampling process (Fig. 1). By doing so, sampling and ionization can be independently optimized, resulting in much more efficient ionization and more quantitative measurements with less matrix effects.

The advantages of the LA ICP-MS can be seen when analyzing high dose BF_2 implants, which usually present a special challenge with the SIMS technique [5]. Because the highly electronegative fluorine in silicon can enhance yields of positive secondary ions during conventional SIMS analysis, a special compensation technique called "O₂-leak" or "oxygen flood" has to be used by SIMS analysts to reduce this enhancement effect [5]. **Figure 3** shows the results obtained with low energy B^+ and BF_2^+ implanted at $1.0\text{E}15$ atoms/cm². Because no fluorine matrix effect is observed, identical dose results were obtained for both implants.

The effect of thermal annealing was also studied using LA ICP-MS; **Fig. 4** shows results with ULE As^+ implanted at $2.0\text{E}15$ atoms/cm² before and after a thermal annealing process. The identical dose concentrations ($2.1\text{E}15$ atoms/cm²) indicate that Saris results are not affected by thermal annealing. Also, $^{75}\text{As}^+$ ions in As^+ implants are directly and reliably measured by the technique. Because the ICP ionization source produces essentially singly charged atomic ions, the $^{29}\text{Si}^{30}\text{Si}^{16}\text{O}^+$ molecular interference at m/z 75 that SIMS encounters [5] was not

observed in the new method. Use of $^{103}\text{AsSi}^-$ molecular ion for implant dose measurements by SIMS, especially for ULE implants, can also be problematic due to the presence of native oxides on wafer surfaces [6]. Because it is very difficult to control native oxide growth on wafers during cleaning and surface preparation prior to ion implantation [6], the resultant variation in native oxide thickness on wafers can alter the ion yield of $^{103}\text{AsSi}^-$ in SIMS measurements. In fact, both enhancement and suppression in $^{103}\text{AsSi}^-$ ion yield by SIMS have been reported. Using atomic $^{75}\text{As}^+$ ion for ULE As dose measurement, such a surface oxide effect is successfully avoided.

Contamination monitoring

In addition to dopant dose measurement for ULE ion implantation, LA ICP-MS can also be used to simultaneously monitor all metallic contaminants without ion source modification. The metal contaminants commonly found in the substrate during ion implantation include aluminum (Al), iron (Fe), chromium (Cr), nickel (Ni), and titanium (Ti). Inadvertent contamination due to either sputter erosion or implanter construction material out-gassing can adversely affect electric properties of devices. This measurement method has been found to be helpful to engineers in evaluating multipurpose ion implanters to avoid unintentional dopant cross contamination during ion implantation.

Conclusion

Utilizing a different solid sampling strategy and an efficient ionization process, an alternative dose-analysis methodology has been developed for quantitative analysis of LE and ULE shallow implants. Although typically the domain of SIMS, the coupling of LA for sampling and detection via ICP-MS permits advantages and functionality not previously available. These advantages include extremely fast sample analysis and the simultaneous availability of all metallic contamination concentrations without ion source modification. More important, quantification of total dopant doses by LA ICP-MS does not depend on depth profiling resolution and surface condition, thereby ensuring the measurement accuracy for ULE implants. Total dose data obtained for ultra shallow $^{11}\text{B}^+$ and $^{75}\text{As}^+$ implants show the measurement technology is not affected by surface oxides on the wafer, the thermal annealing process, or the presence of co-implanted species such as high concentration fluorine, a feature very important when analyzing high dose BF_2^+ ion implants.

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